

# Harmonic Filter Topologies for Low DC Bus Capacitance of 6-Pulse Rectifier Front End Adjustable Speed Drives

Tin Luu

Senior Product Engineer  
MTE Corporation  
Menomonee Falls WI, USA  
Tin.luu@mtecorp.com

Todd Shudarek

Director of Engineering  
MTE Corporation  
Menomonee Falls WI, USA  
Todd.shudarek@mtecorp.com

**Abstract**—Passive harmonic filter topologies that mitigate harmonic problems in three-phase power system due to low DC bus capacitance of 6-pulse rectifier front end adjustable speed drives are proposed. The first filter topology is the modified typical LLCL harmonic filter with a capacitor added across the input and output reactors of each phase. The second filter topology is also LLCL harmonic filter with a capacitor and damping resistor added in series across the input and output reactors of each phase. Both topologies create high order filters. The filter transfer functions are derived. A prototype was constructed and tested with the results presented. Simulation results correlated well with the prototype test data. The prototype filter for both topologies reduced the total harmonic current distortion (THID) below 5% to meet the limits of IEEE 519.

**Keywords**— 6-pulse rectifier front end; adjustable speed drives (ASD); LLCL harmonic filter

## I. INTRODUCTION

The function of the drive is to convert a fixed voltage and frequency from an electrical power source into a variable voltage and frequency for controlling an AC motor. Any variable frequency drive (VFD) is comprised of three sections: the rectifier, DC bus, and inverter. The rectifier section is used to convert the fixed incoming AC line voltage into a DC bus voltage. Low power drives use a diode rectifier and resistors to charge the bus capacitors. Two rectifiers are required for each phase of power [1]. The circuit representation for this drive technology is shown in Fig. 1. The medium and high power drives use silicon-controlled rectifiers (SCRs) to control the charging of the bus capacitors. A link choke and DC bus capacitors in the drives form a filter that smooth the output voltage of the rectifier into a steady DC voltage. An optional dynamic brake device on these drives allows regenerative energy from the load to be dissipated in an external resistor when the drive is braking [1]. The circuit representation for this drive technology is shown in Fig. 2. Another type of rectifier is called converter or active front-end rectifier. A converter section is used on the drives to regulate power flow between the AC line and DC bus. The converter uses an insulated gated bipolar transistor (IGBT) bridge to rectify the

AC line voltage into a DC bus voltage. This section also regenerates energy from the DC bus to the AC line when the drive is braking [1]. The circuit representation for this drive technology is shown in Fig. 3.

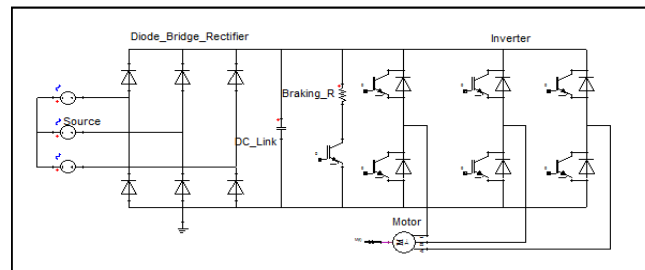


Fig. 1. Diode bridge rectifier

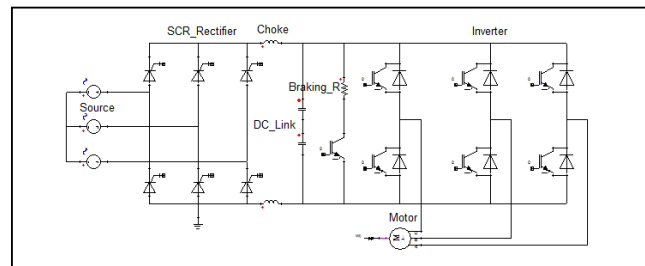


Fig. 2. SCRs rectifier

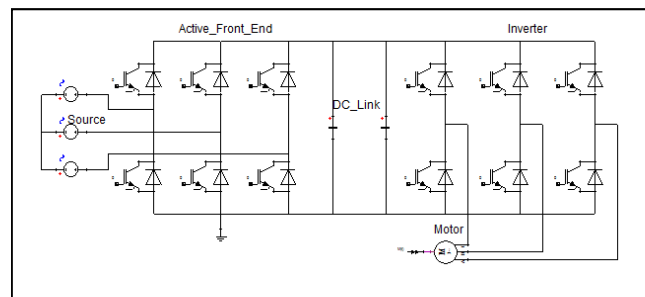


Fig. 3. Active front end rectifier

There has been a recent trend of many drive manufacturers to offer lower cost, more compact, adjustable speed motor drives with lower DC bus capacitance. The lower DC bus capacitance drives interact with current existing harmonic filter products causing significant higher THID compared to the regular drives. It reduces the effectiveness of the function of passive harmonic filters. Now many of the existing passive filters used with adjustable speed drives that guarantee less than 5% THID are no longer meet the strictest requirement of IEEE 519. This paper proposes a method [2] to modify an existing LLCL filter topology to make it suitable to meet IEEE 519 [3]. This paper also performs an analysis of the filtering solution. An experimental filter based on the proposed solution is built and tested with a low DC bus capacitance drive system.

## II. BASIC STRUCTURE OF PROPOSED FILTER

### A. Proposed Filter Circuit and Components for Topology # 1

The circuit of the proposed filter is shown in Fig. 4. L1A, L1B and L1C are inductors of the input coils. L2A, L2B and L2C are inductors of the output coils. L3A, L3B and L3C are inductors of the shunt coils. These coils use LLCL filter technique discussed in [4]. C3A, C3B and C3C are the tuning capacitors of the existing harmonic filter. C1A, C1B and C1C are the main capacitors of the topology # 1.

### B. Proposed Filter Circuit and Components for Topology # 2

The circuit of the proposed filter is shown in Fig. 5. The input, output and shunt coils are similar to topology # 1. C3A, C3B and C3C are the tuning capacitors of the existing harmonic filter. C1A, C1B and C1C are the main capacitors of the topology # 2. R1A, R1B and R1C are damping resistors.

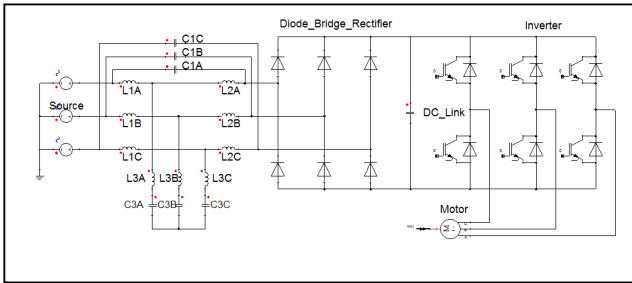


Fig. 4. Filter circuit and components of topology # 1

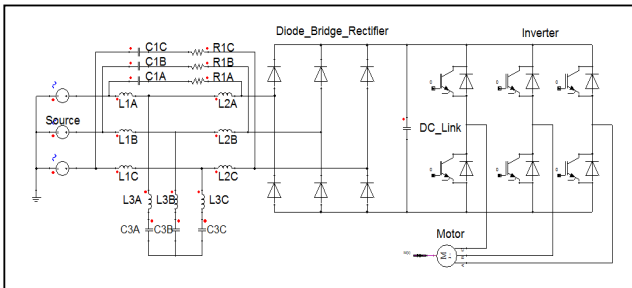


Fig. 5. Filter circuit and components of topology # 2

## III. THEORETICAL ANALYSIS OF PROPOSED FILTER

### A. Transfer Function of Typical LLCL Harmonic Filter

The following per-phase equivalent circuit of the typical LLCL harmonic filter is shown in Fig. 6.  $L_i$  is the rectifier or inverter side inductor,  $L_g$  is the grid side inductor,  $L_f$  is shunt inductor series with the shunt capacitor  $C_f$ .  $V_i$  is the rectifier voltage or inverter voltage.  $I_i$ ,  $I_f$  and  $I_g$  are the rectifier, shunt and grid currents.  $V_a$  is the shunt voltage. The transfer function  $I_g/V_i$  ratio is calculated by using Kirchoff's laws [5]. For the consistence of the current direction, the sign convention is used as shown in Fig. 6. In order to derive the transfer function of the filter, some mathematical calculations have to be made. The grid voltage is assumed to be an ideal voltage source and it represents a short circuit for harmonic frequencies, and for the filter analysis it is set to zero [6]. Applying Kirchoff's current and voltage law at node  $V_a$ , the filter model in s-plane can be written with the following equations:

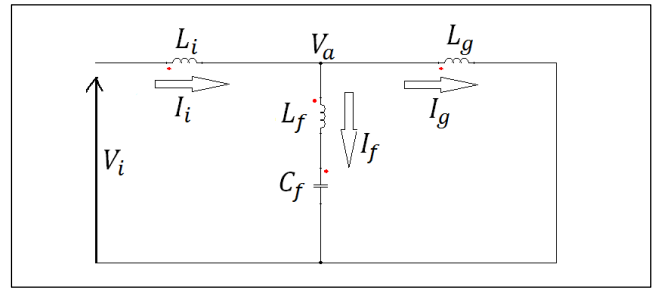


Fig. 6. Per-phase equivalent circuit of typical LLCL harmonic filter

$$I_i = I_f + I_g \quad (1)$$

$$V_i - V_a = I_i S L_i \quad (2)$$

$$V_a = I_g S L_g \quad (3)$$

$$V_a = I_f \left( \frac{1}{S C_f} + S L_f \right) = I_f \left( \frac{S^2 L_f C_f + 1}{S C_f} \right) \quad (4)$$

$$I_g S L_g = I_f \left( \frac{S^2 L_f C_f + 1}{S C_f} \right) \quad (5)$$

Equation (2) can be written as:

$$V_i = I_g S L_g + (I_f + I_g) S L_i \quad (6)$$

$$V_i = I_g \left( S L_g + \left( 1 + \frac{S^2 L_g C_f}{S^2 L_f C_f + 1} \right) S L_i \right) \quad (7)$$

$$H_{LLCL} = \frac{I_g}{V_i} = \frac{1}{S L_g + \left( 1 + \frac{S^2 L_g C_f}{S^2 L_f C_f + 1} \right) S L_i} \quad (8)$$

The final transfer function of the filter can be calculated as

$$H_{LLCL} = \frac{I_g}{V_i} = \frac{S^2 L_f C_f + 1}{S^3 (L_g L_f C_f + L_i L_f C_f + L_g L_i C_f) + S(L_g + L_i)} \quad (9)$$

The resonant frequency  $f_r$  can be derived in (10).

$$f_r = \frac{1}{2\pi \sqrt{\left(\frac{L_g L_i}{L_g + L_i} + L_f\right) C_f}} \quad (10)$$

From the transfer function in (9), the typical LLCL filter is the third order filter and the tuning frequency is around 300 Hz from frequency response in Fig. 7.

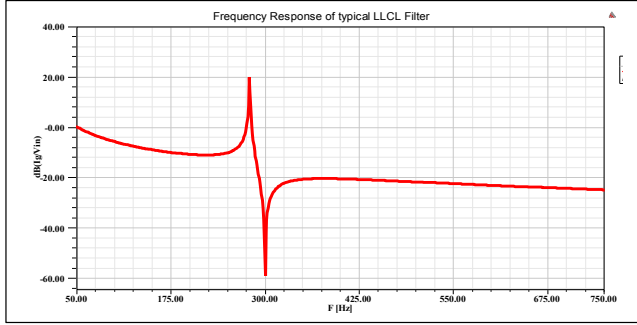


Fig. 7. Frequency response of a typical LLCL harmonic filter

### B. Transfer Function of Harmonic Filter Topology # 1

The following per-phase equivalent circuit of modified LLCL harmonic filter topology # 1 is shown in Fig. 8.

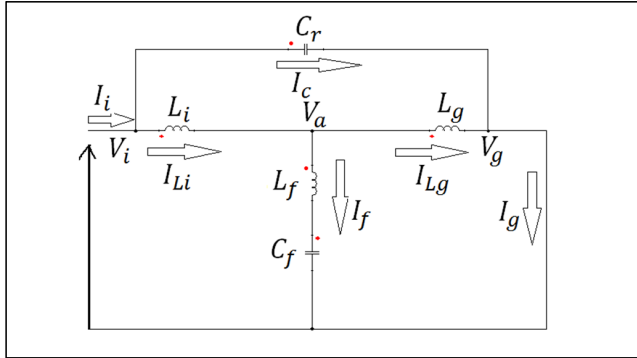


Fig. 8. Per-phase equivalent circuit for topology # 1

$L_i$  is the rectifier or inverter side inductor,  $L_g$  is the grid side inductor,  $L_f$  is the shunt inductor series with the shunt capacitor  $C_f$ .  $C_r$  is the bridge capacitor that connects across the  $L_i$  and  $L_g$  inductors.  $I_{L_i}$  is the current of  $L_i$  inductor,  $I_f$  is the current of the shunt,  $I_{L_g}$  is the current of the  $L_g$  inductor,  $I_i$  is the current of the rectifier or inverter,  $I_c$  is the current of the bridge capacitor and  $I_g$  is the current of the grid.  $V_i$  is the rectifier voltage or inverter voltage.  $V_a$  is the shunt voltage and  $V_g$  is the grid voltage. The grid voltage is assumed to be an ideal voltage source and it represents a short circuit for harmonic frequencies, and for the filter analysis it is set to zero [6]. For the consistence of the current direction, the sign convention is used as shown in Fig. 8. The transfer function  $I_g/V_i$  ratio is calculated by using Kirchoff's laws [5]. Applying Kirchoff's current and voltage laws at the node  $V_i$ ,  $V_a$  and  $V_g$ , the filter model in s-plane can be written with the following equations:

$$I_i = I_c + I_{L_i} \quad (11)$$

$$I_{L_i} = I_f + I_{L_g} \quad (12)$$

$$I_g = I_c + I_{L_g} \quad (13)$$

$$\frac{V_i - V_a}{S L_i} = \frac{V_a}{S L_f + \frac{1}{S C_f}} + \frac{V_a}{S L_g} = \frac{V_a C_f S}{L_f C_f S^2 + 1} + \frac{V_a}{S L_g} \quad (14)$$

Simplifying (14), the (15) is calculated as following

$$\frac{V_i}{S L_i} = V_a \left( \frac{1}{S L_i} + \frac{1}{S L_g} + \frac{S C_f}{S^2 L_f C_f + 1} \right) \quad (15)$$

Simplifying the algebraic expression of (15) in term of S the following expressions can be used for calculating the final transfer function.

$$\frac{V_i}{S L_i} = V_a \left( \frac{S^2 (L_f C_f L_g + L_f C_f L_i + L_i L_g C_f) + (L_g + L_i)}{S^3 L_f C_f L_i L_g + S L_i L_g} \right) \quad (16)$$

Equation (13) can be written as:

$$I_g = I_c + I_{L_g} = \frac{V_i}{\frac{1}{S C_r}} + \frac{V_a}{S L_g} \quad (17)$$

From (17),  $V_a$  can be calculated in term of  $I_g$  and  $V_i$ .

$$V_a = S L_g I_g - S^2 L_g C_r V_i \quad (18)$$

The specific transfer function (19) is calculated by substituting (18) into (16) and simplifying the algebraic expression in terms of the ratio  $I_g/V_i$ .

$$H_{topology_1} = \frac{I_g}{V_i} = \frac{A * S^4 + B * S^2 + 1}{C * S^3 + D * S} \quad (19)$$

The coefficients A, B, C, and D are calculated as

$$A = C_r (L_f C_f L_g + L_f C_f L_i + L_i L_g C_f)$$

$$B = L_f C_f + (L_g + L_i) C_r$$

$$C = L_f C_f L_g + L_f C_f L_i + L_i L_g C_f$$

$$D = L_g + L_i$$

The frequency response of both LLCL filter and topology # 1 filter on the same plot for comparison is in Fig. 9.

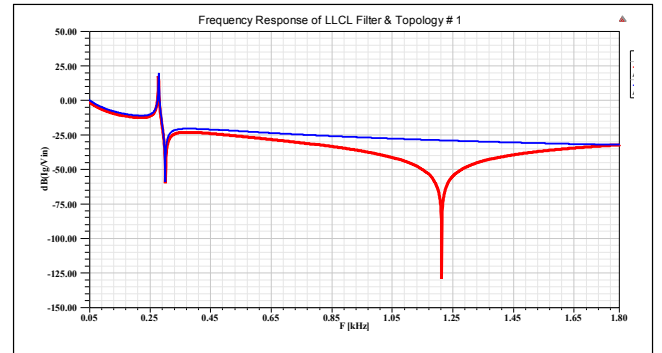


Fig. 9. Frequency response of both LLCL filter and topology # 1 filter

Fig. 7 shows a typical frequency response of the LLCL filter. The dominant 5<sup>th</sup> harmonic has the most attenuation and the frequencies beyond the 5<sup>th</sup> are attenuated less. Fig. 9 shows the frequency response with only adding the bridge capacitors consistent with the teaching of this method. There is an additional zero in the transfer function near the 19<sup>th</sup> harmonic. There is also additional attenuation at all of the other frequencies between the 5<sup>th</sup> and 19<sup>th</sup> harmonic. Note that the additional bridge capacitors did not move the zero in the transfer function near the dominant 5<sup>th</sup> harmonic. This allows an existing filter to be easily improved for a minimal cost to make suitable for applications with low DC bus capacitance.

### C. Transfer Function of Harmonic Filter Topology # 2

The per-phase equivalent circuit of the modified LLCL harmonic filter topology # 2 is shown in Fig. 10. All the components of the filter topology # 2 are identical to topology # 1 except  $C_r$  is now connected in series with  $R_d$  across the  $L_i$  and  $L_g$  inductors.

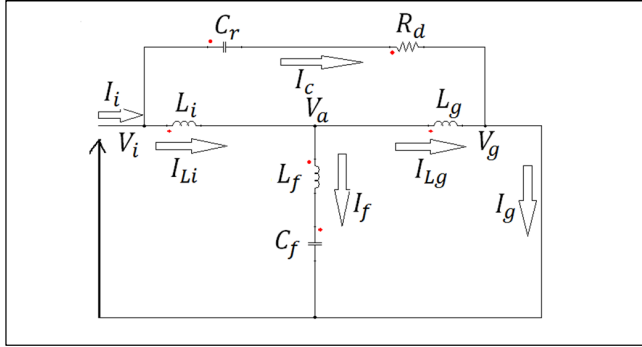


Fig. 10. Per-phase equivalent circuit for topology # 2

Using the same method applied in topology #1, the following expressions can be used for calculating the transfer function of topology # 2. Equation (13) can be written as:

$$I_g = I_c + I_{Lg} = \frac{V_i}{\frac{1}{SC_r} + R} + \frac{V_a}{SL_g} \quad (20)$$

From (20),  $V_a$  can be calculated in term of  $I_g$  and  $V_i$ .

$$V_a = \frac{SL_g(1 + R_d C_r S)}{1 + R_d C_r S} I_g - \frac{C_r L_g S^2}{1 + R_d C_r S} V_i \quad (21)$$

The specific transfer function (22) is calculated by substituting (21) into (16) and simplifying the algebraic expression in terms of the ratio  $I_g/V_i$ .

$$H_{topology_2} = \frac{I_g}{V_i} = \frac{A * S^4 + B * S^3 + C * S^2 + D * S + 1}{E * S^4 + F * S^3 + G * S^2 + H * S} \quad (22)$$

Coefficients A, B, C, D, E, F, G and H are calculated as

$$A = C_r(L_f C_f L_g + L_f C_f L_i + L_i L_g C_f)$$

$$B = L_f C_f C_r R_d$$

$$C = L_f C_f + (L_g + L_i) C_r$$

$$D = C_r R_d$$

$$E = C_r R_d (L_f C_f L_g + L_f C_f L_i + L_i L_g C_f)$$

$$F = L_f C_f L_g + L_f C_f L_i + L_i L_g C_f$$

$$G = (L_g + L_i) C_r R_d$$

$$H = L_g + L_i$$

A typical frequency response for the low DC bus capacitance topology # 2 is shown in Fig. 11. The frequency response of both the LLCL harmonic filter (in Blue) and topology # 2 filter (in Red) is shown on the same plot for comparison is in Fig. 12.

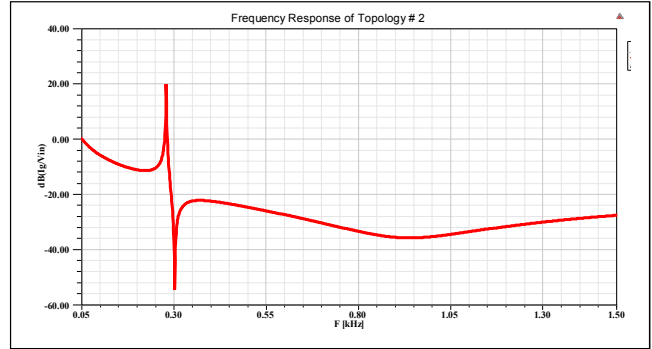


Fig. 11. Frequency response of topology # 2

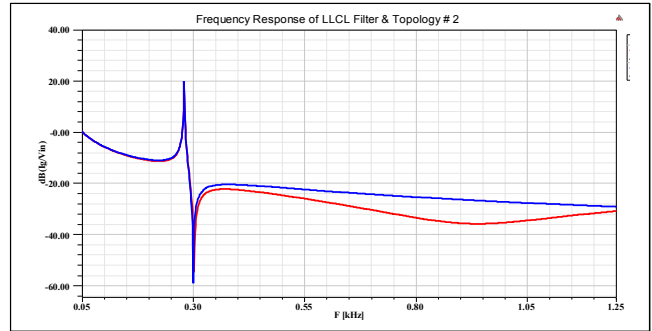


Fig. 12. Frequency response of both LLCL filter and topology # 2 filter

### D. Filter Design Example

An example filter is designed with the system parameters in Table I. The filter design parameters for LLCL harmonic filter, topology # 1 and topology # 2 are shown in Table II, Table III and Table IV. Topologies #1, # 2 and the typical LLCL filter use a 66A filter rating. The inductance parameters were determined by using finite element analysis magnetics software.

TABLE I. TEST SYSTEM PARAMETERS

System Voltage	480 V
Fundamental frequency	60 Hz
PWM carrier frequency	2 kHz
VFD sample A	50 HP
Motor rating	50HP

TABLE II. FILTER PARAMETERS FOR ADAPTIVE PASSIVE TECHNIQUE

$L_I$	Input inductance	1.560 mH
$L_O$	Output inductance	0.503 uH
$L_S$	Shunt inductance	2.426 mH
$C_S$	Shunt capacitance	120.0 uF

TABLE III. FILTER PARAMETERS FOR TOPOLOGY # 1

$L_I$	Input inductance	1.560 mH
$L_O$	Output inductance	1.143 uH
$L_S$	Shunt inductance	2.426 mH
$C_S$	Shunt capacitance	120.0 uF
$C_R$	Bridge capacitance	7.5 uF

TABLE IV. FILTER PARAMETERS FOR TOPOLOGY # 2

$L_I$	Input inductance	1.560 mH
$L_O$	Output inductance	0.503 uH
$L_S$	Shunt inductance	2.426 mH
$C_S$	Shunt capacitance	120.0 uF
$C_R$	Bridge capacitance	30.0 uF
$R_D$	Damping resistance	6.0 $\Omega$

IV. SIMULATION RESULTS

Simulations and comparison study on the effect of the LLCL harmonic filter, filter topology # 1, and topology # 2 on the new low DC bus capacitance of variable frequency drives were carried out. A completed filter simulation system comprises of VFD sample A, a three-phase reactor, shunt capacitors, bridge capacitors, a damping resistor and 50HP motor. The system is simulated by using Ansys Simplorer as shown in Fig. 4 and Fig. 5. Fig.13-21 are obtained showing the input, output current waveforms, the spectral of currents, and THID before and after using the LLCL harmonic filter, topology #1 filter, and topology # 2 filter.

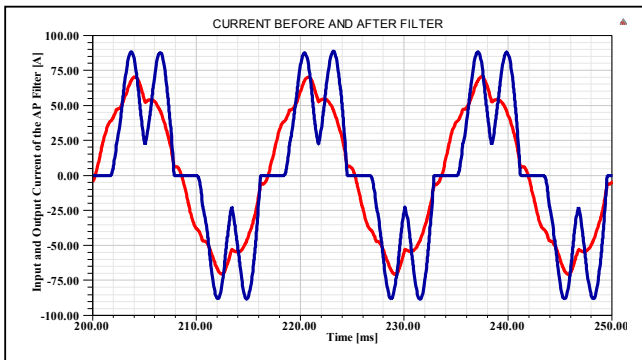


Fig. 13. Input and output currents of the LLCL harmonic filter

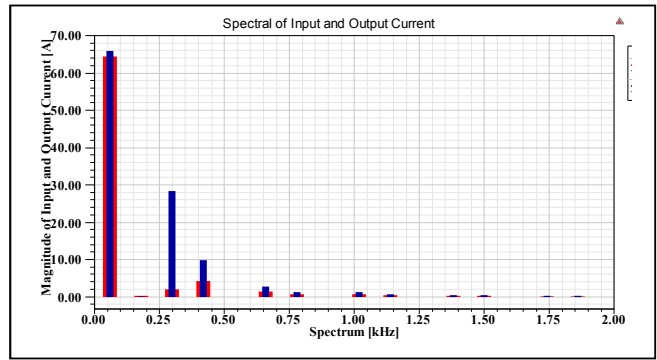


Fig. 14. Spectral of input and output currents of the LLCL harmonic filter

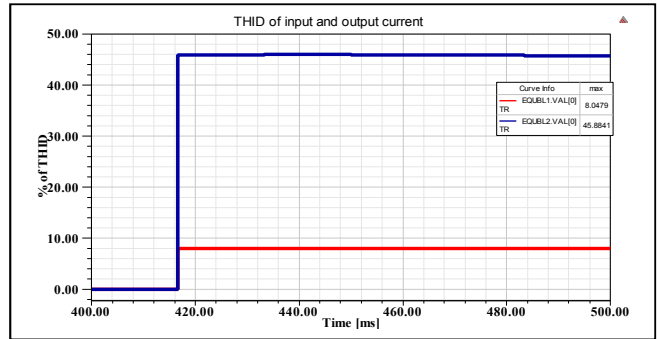


Fig. 15. THID of input and output currents of the LLCL harmonic filter

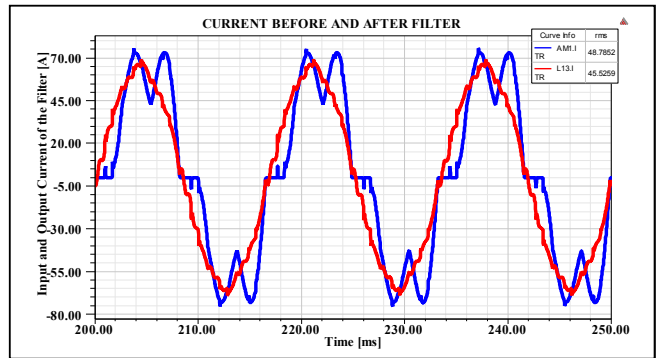


Fig. 16. Input and output currents of harmonic filter topology # 1

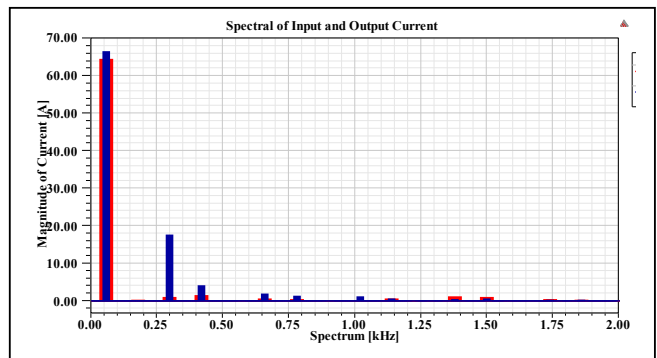


Fig. 17. Spectral of input and output currents of harmonic filter topology # 1

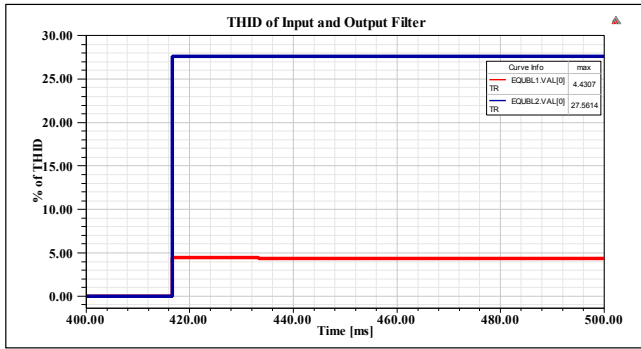


Fig. 18. THID of input and output currents of harmonic filter topology # 1

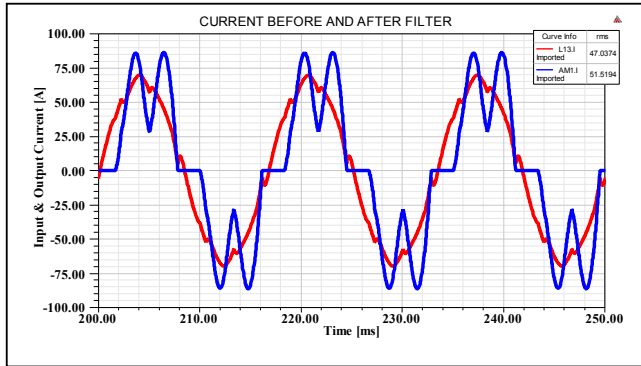


Fig. 19. Input and output currents of harmonic filter topology # 2

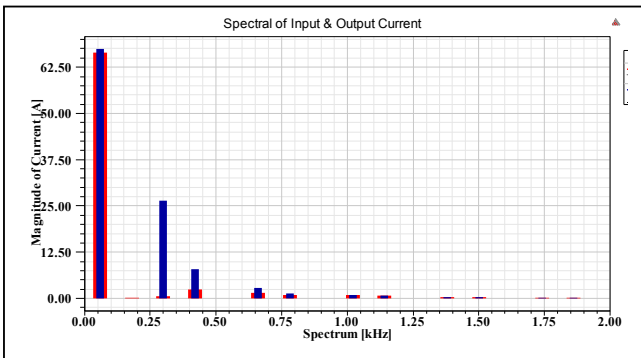


Fig. 20. Spectral of input and output currents of harmonic filter topology # 2

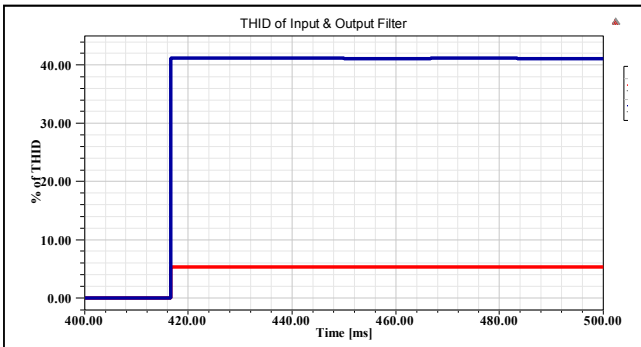


Fig. 21. THID of input and output currents of harmonic filter topology # 2

The system has been modeled using Ansys Simplorer and shown in Figs. 13-21. At 75% load, THID performance of the LLCL filter is 8.05%. That exceeds the IEEE 519 standard. The low DC bus capacitance VFD affected the harmonic performance of the LLCL filter and all harmonic filters in general. The modified filters were developed by using the existing LLCL filter and are called topology # 1 and topology # 2 filters. At the same load, THID performance of topology # 1 and topology # 2 are 4.43% and 5.50% accordingly. The summary of the simulation results is in Table. V.

TABLE V. SIMULATION RESULTS DATA

	THID AT 75% LOAD
AP Filter	8.05%
TOPOLOGY # 1	4.43%
TOPOLOGY # 2	5.50%

## V. EXPERIMENTAL RESULTS

The experimental setup was built in the laboratory of MTE Corporation consisting of a 480V 60Hz three-phase power supply, a commercial 50HP VFD sample A, a 66A harmonic filter and 50HP motor. The experimental results were performed with the system parameters in Table I and filter parameters in Tables II-IV. The laboratory conducted experiments with the LLCL, topology #1 and topology # 2 filters. The experimental filters are shown in Figs. 22-23. Table VI shows THID experiment results of the LLCL, topology # 1 and topology # 2 filters. Since the maximum motor load current is 55A and the filter rating is 66A, the maximum percentage of load current the motor can reach is 83%. At 75% load, the THID performances of the LLCL, topology #1, topology # 2 filters are 9%, 4.9% and 5.9%. Figs. 24-27 show the waveforms of input and output filter currents, and the DC bus voltage of the LLCL, topology # 1 and topology # 2 filters. These experimental results correlated well with the simulation results and data shown in Table V.



Fig. 22. Experimental of 50HP VFD sample A

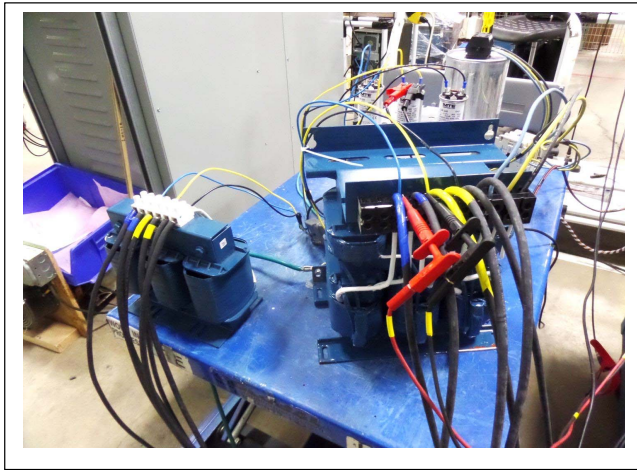


Fig. 23. Experimental filter

TABLE VI. EXPERIMENTAL RESULTS DATA

	THID AT 75% LOAD
AP Filter	9.0%
TOPOLOGY # 1	4.9%
TOPOLOGY # 2	5.9%

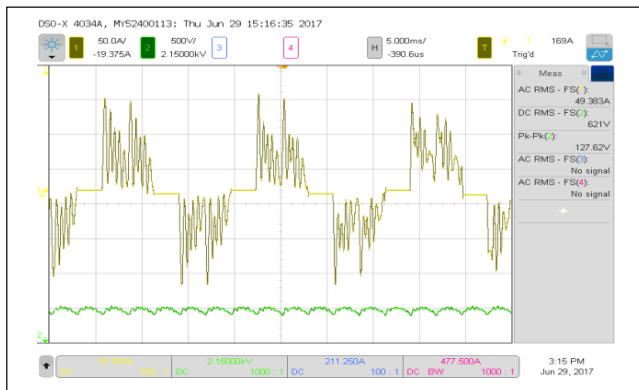


Fig. 24. The input current of low DC bus capacitance VFD without filter

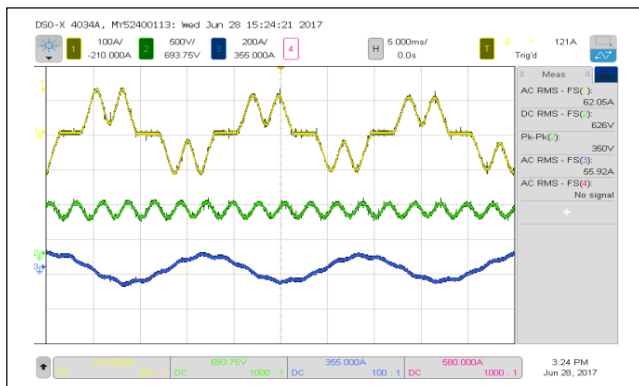


Fig. 25. The input and output currents of the LLCL filter

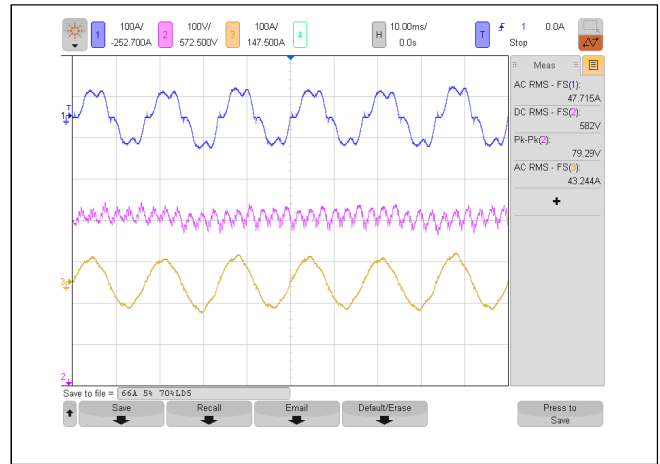


Fig. 26. The input and output currents of filter topology # 1

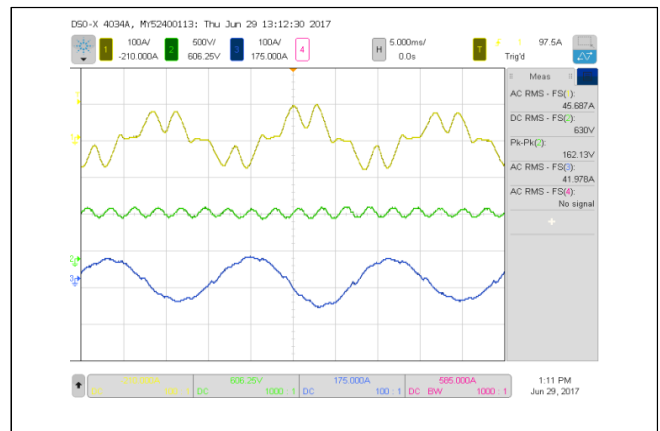


Fig. 27. The input and output currents of filter topology # 2

Tables VII-IX show the numerical results of speed, the percent of the load, input and output currents, the percent THID and the DC bus voltage of the LLCL filter, topology # 1 filter, and topology # 2 filter.

TABLE VII. EXPERIMENTAL RESULTS DATA FOR AP FILTER

Speed (rpm)	Input Current (A)	Output Current (A)	THID (%)	DC Bus Voltage (V)	Load (%)
1808	16	17	14	640	20
1818	26	27	12	623	40
1832	39	42.5	10	605	64
1842	50	52	9	592	78
1844	52	56	8	589	85

TABLE VIII. EXPERIMENTAL RESULTS DATA FOR TOPOLOGY #1 FILTER

Speed (rpm)	Input Current (A)	Output Current (A)	THID (%)	DC Bus Voltage (V)	Load (%)
1808	17.0	14.2	10.5	640	21
1818	26.3	27.4	8.5	612	41
1826	33.6	36.3	6.5	600	54
1832	38.6	42.0	5.6	590	63
1836	43.0	46.8	5.3	582	70
1840	47.0	51.0	4.9	573	77
1844	51.0	55.0	4.8	567	83

TABLE IX. EXPERIMENTAL RESULTS DATA FOR TOPOLOGY #2 FILTER

Speed (rpm)	Input Current (A)	Output Current (A)	THID (%)	DC Bus Voltage (V)	Load (%)
1808	18.0	16.4	10.8	650	25
1818	28.0	31.0	8.2	635	47
1826	37.0	40.7	7.3	633	62
1832	44.0	48.5	6.8	631	73
1836	48.0	53.0	5.9	629	80
1840	52.0	58.0	5.3	625	88
1844	57.0	63.0	4.8	620	95

The numerical results in Tables VII-IX show that at low percentage of load current (less than 30%), THID performance improves comparing to the other harmonic filters since adaptive passive technique is used in the reactor manufacturing process. This technique increased the inductance value by 50% at low percentage of load current. At higher than 30% load, becomes progressively lower.

## VI. CONCLUSION

In the past, motor drives typically have had about 30-50uF of capacitance per horsepower. Some of these newer low cost drives have DC bus capacitances as low as 5uF per horsepower such as that in the 50HP VFD sample A. At the lower DC bus capacitance level, the harmonic currents at the

5<sup>th</sup> and 7<sup>th</sup> harmonic increase significantly. This increase in harmonic currents and the negative effect of the interaction between the new drives with the current harmonic filters illustrate the need for this invention. Drive filters such as the LLCL harmonic filter can be very effective at reducing the THID down to low levels at both full and reduced loads to meet the 5% THID requirements of IEEE 519 but having difficulty with low DC bus capacitance VFDs.

The modeling and analysis of the LLCL, topology #1 and topology # 2 filters for low DC bus capacitance drive applications have been presented. The transfer functions of the LLCL, topology # 1 and topology # 2 filters have been verified and demonstrated in a very simple form of a third and fourth order filters. Simulation and experimental results of the prototypes have shown that the proposed (topology # 1 and topology # 2) filters are capable of reducing the THID performance of the LLCL filter with a low DC bus capacitance drive to less than 5%. It is also proven the higher output inductance values of topology # 1, damping resistor of topology # 2 and the bridge capacitors are the main components that differentiated the proposed filters from the typical LLCL filter.

The performances of the proposed filters have been evaluated with a 480V 60Hz 50HP system of VFD sample A and 50HP motor load. The experimental results obtained in the laboratory confirmed the validity of the simulation model developing using the Ansys Simplorer software. The future work in this project is to test the performance of these filter topologies with many more low DC bus capacitance drives such as VFD sample B, and C as shown in Table X. The results of these tests will help the design engineers to come up with complete solutions for this problem.

TABLE X. DC BUS CAPACITANCE VALUES FOR SAMPLES VFD

VFD SAMPLE	DC BUS CAPACITANCE VALUE PER HP (uF)
A	5
B	14
C	2

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